AN OPEN-SOURCE SIMULATION TOOL OF GRID-CONNECTED PV SYSTEMS

J. Muñoz
Instituto de Energía Solar. Universidad Politécnica de Madrid (IES-UPM)
Address: Avenida Complutense, 30. Ciudad Universitaria. 28040 Madrid. E-mail: javier@ies-def.upm.es
L. Marroyo
Universidad Pública de Navarra, Spain
M. Collares-Pereira
Universidade de Evora, Portugal
N. Tyutyuyndzhiev
Central Laboratory of Solar Energy and New Energy Sources, Bulgary
M. Conlon
Dublin Institute of Technology, Ireland
A. Elmoussaoui
Office National d'Electricité, Morocco
B. Wilkin
Association pour la promotion des energies renouvelables, Belgium

ABSTRACT: This paper presents the features, models, and calculation procedures implemented in an open-source simulation tool of grid-connected PV systems, which is being developed under the support of a European project. Simulations may be carried out with different time series of input data coming from the monitoring of PV systems, ground-based weather stations, satellite measurements or popular databases. Besides, the tool may also generate the required time series starting from monthly averages of irradiance and ambient temperature values. Models of components are mainly based on standard information, provided by manufacturers or promoters, which may be verified experimentally by on-site quality control testing procedures. Among other simulation options, it is possible to select between three static PV generators (ground, roof or façade) or six trackers (with/without backtracking), and to carry out different types of analysis (sweep, parametric, ensembles, etc.). The tool provides, among other simulation results, the energy yield, the analysis and breakdown of energy losses, and the estimations of financial returns adapted to the legal and financial frameworks of each European country. Besides, educational facilities will be developed and integrated in the tool, not only devoted to learn how to use the software, but also to train the users on the best design PV systems practices.
Keywords: Grid-Connected, PV System, Simulation

1 INTRODUCTION

This paper describes the features of an open-source simulation tool of grid-connected PV systems, which is being developed under the support of an European research project called PVCROPS [1].

The tool, whose first version will be available on-line at the end of October 2013 at the website of PVCROPS [2], allows the modeling and the design of different types of grid-connected PV systems, such as large grid-connected plants and building-integrated installations (BIPV).

The tool is based on a previous software developed by the IES-UPM [3][4], whose models and energy losses scenarios have been validated in the commissioning of several PV projects [5] carried out in Spain, Portugal, France and Italy, whose aggregated capacity is nearly 300MW. This link between design and commissioning is one of the key points of the tool presented here, which is not usually addressed by present PV simulation software packages.

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The tool has taken into consideration the recommendations of several PV community experts, which have been invited to identify present necessities in the field of PV systems simulation. For example, the possibility of using meteorological forecasts as input data or modeling the integration of energy storage.

Figure 1 displays the general configuration of the simulated grid-connected PV system, which is composed of a PV generator, inverter (MPPT + DC/AC converter), energy storage, and a low voltage/medium voltage (LV/MV) transformer.

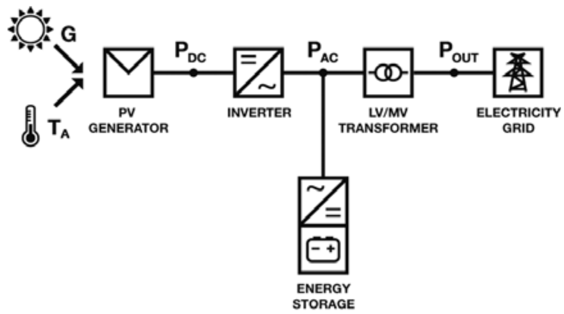

Figure 1: General configuration of the simulated grid-connected PV system.

Simulations start from time series of irradiance, cell temperature and wind speed for a specified period of analysis (typically a day, a month or a year) and a given simulation step, which may range from seconds to hours. In particular, simulations may also be carried out with instantaneous values, which may be used for real-time analysis. Besides, if time series are not available, the program generates them starting from mean or average values.

Next sections describe the system modeling and calculation procedures, the available types of analysis, and output results.

2 SYSTEM MODELING AND CALCULATION PROCEDURES

This section describes the models and calculation procedures that have been implemented in the simulation tool, which constitute the core of the open source code, whose first version has been written in the PHP programming language.

2.1 Generation of time series

As mentioned above, the simulation runs with time series of irradiance, cell temperature, and wind speed. For example, from the monitoring of a grid-connected PV plant. Besides, when times series are not available, the program may generate them starting from mean values.

Regarding irradiance, the most common available information for any site is the 12 monthly mean values of global horizontal daily irradiation. These data, as well other required input parameters, can be introduced by the user through a web interface (Figure 2 shows a screenshot) or automatically imported from popular databases, such as PVGIS [6], selecting the site using Google Maps© applications [7].

Next, a time series of horizontal radiation is generated using different models proposed in the literature. The most common approach involves two steps. First, daily horizontal global irradiation components (beam and diffuse) are calculated using global-diffuse correlations, for example, those of Page [8], Erbs [9] or Macagnan [10]. Second, instantaneous values of beam and diffuse irradiances are calculated from the previous irradiation components as described by Collares-Pereira and Rabl [11].

Other implemented approaches generates the horizontal time series considering clear sky models [12], which required extra information about Linke turbidity, a combination of clear and cloudy skies, or synthetic generation [13][14].

The tool may carry out the simulations starting from previously generated or measured time series from databases of Typical Meteorological Years [15], monitoring of PV systems, ground-based weather stations or satellite measurements.

Figure 2: Screenshot of the input data web interface.

Normally, two final calculation steps are required, the translation of irradiance values from the horizontal surface to the plane of PV modules and the discount of power losses caused by shading, dirt, incidence and spectrum. For this purpose, the following sequence of calculations, based on previous work [3][4], has been implemented:

1. Position of the Sun, position of the PV generator surface, and incidence angle [16].
2. Shaded surface on the PV generator.
3. Irradiance on the PV generator plane [17][18].
4. Dirt and incidence losses [19].
5. Shading losses [20].
6. Spectral corrections [21].

Regarding cell temperature, the most common practice is to start from the ambient temperature, T_A, and derive the cell temperature, T_C, using the well-know equation:

$$T_C = T_A + \frac{NOCT - 20}{800} G \qquad (1)$$

Where $NOCT$ is the nominal operation cell temperature obtained from the manufacturer datasheet, in ºC, and G is the irradiance, in W·m^{-2}.

In the last years, direct measurements of the cell temperature are also available from the monitoring of some grid-connected PV systems. Such measurements are normally performed either attaching a temperature sensor (thermocouple or similar) to the back surface of the modules or calculating it from the measurements of the open-circuit voltage of a reference module [5].

If time series of ambient or cell temperature are not available, the program generates them starting from the monthly average of the minimum and maximum daily ambient temperatures [16].

Regarding wind speed, the program accepts as input previously generated time series of data, which allows, for example, to use models more sophisticated than Equation (1) for calculating the cell temperature [22].

Finally, it is worth stressing that most of the implemented models are mainly based on standard information provided by manufacturers, promoters, etc. This allow to strengthen the above mentioned link between simulations results and on-site quality control testing procedures, which allow to verify if the assumed simulation hypothesis are fulfilled in the field.

2.2 PV modules and generators

Different technologies of PV modules may be simulated (Si-c, Te-Cd, Si-a, III-V, and CIS), whose maximum output power, P_{DC}, is calculated using this equation:

$$P_{DC} = P^* \frac{G}{G^*} \frac{\eta}{\eta^*} \qquad (2)$$

Where P^* is the maximum power under standard test conditions (STC, defined by a normal irradiance of G^*=1000W/m^2 and a cell temperature of $T_C^* = 25^{\circ}C$, and AM1.5 spectrum), η is the efficiency as a function of the irradiance and cell temperature T_C, and η^* is the efficiency under STC, $\eta^* = P^*/AG^*$, where A is the active area of the PV generator.

The first and simple implemented model only takes into account the dependence of the efficiency with the temperature:

$$\frac{\eta}{\eta^*} = 1 + \gamma (T_C - T_C^*) \qquad (3)$$

Where γ is the power temperature coefficient of the PV modules, in ºC^{-1}. Despite its simplicity, this model provides good results [23].

The dependence of the efficiency with both the temperature and the irradiance is modeled by:

$$\frac{\eta}{\eta^*} = \left[1 + \gamma (T_C - T_C^*)\right]\left[a + b\frac{G}{G^*} + c\ln\frac{G}{G^*}\right] \qquad (4)$$

The parenthesis on the right-hand side of the previous equation is an experimental model [24], whose parameters *a*, *b*, y *c* must be fitted for each PV module. Normally, the curve of variation of the efficiency with the irradiance is not usually provided by the manufacturer, and the only knew data is the efficiency at 25ºC and 200 W/m^2, η_{200}, whose measurement is performed during the qualification tests of PV modules [25]. Using this single point, a rough approximation for Si-x can be made by selecting a=1, b=0 and:

$$c \cong 0{,}621\left[1 - \frac{\eta_{200}}{\eta^*}\right] \qquad (5)$$

The expansion of the Equation (3) gives a complex polynomial expression that is similar to some experimental models found in the literature [26][27], but with the difference of using parameters only based on manufacturer's information.

Recently, the IEC has published the first part of an standard that deals with the energy rating of PV modules [28], which proposes a power rating model called 'performance surface'. Specialized laboratories have published first results on the application of the previous standard [29][30], but there is not still neither a general consensus nor an experimental validation that justify the very high complexity of the associated testing procedures. Despite of this, it is foreseen to include such complex models as simulation option, in order to compare them with more simple approaches, such as those described by Equations (3) and (4).

Finally, it is worth pointing that three static and six tracking structures are available for simulation, which are indicated in the Table I. These structures are defined by geometric parameters (inclination, separation among structures, maximum rotating angles, etc.) and, in the case of trackers with flat-plate modules, by the possibility of backtracking operation [4].

Table I: Simulated static and tracking structures.

Static	Ground, roof and façade
Tracking	· One axis horizontal or inclined · One axis vertical (azimuthal) · Two axis (1st vertical, 2nd horizontal) · Two axis (1st vertical, 2nd horizontal - Venetian blind type) · Two axis (1st horizontal, 2nd perpendicular) · Two axis concentrator

2.3 Inverter

The inverter is characterized by its nominal output power (P_I) and three experimental parameters (k_0, k_1 and k_2), which are used to calculate its power efficiency, η_I, by means of this equation [31]:

$$\eta_I = \frac{P_{AC}}{P_{DC}} = \frac{p_{ac}}{p_{ac} + (k_0 + k_1 p_{ac} + k_2 p_{ac}^2)} \qquad (6)$$

Where $p_{ac}=P_{AC}/P_I$ being P_{AC} the output AC power of the inverter, which can be determined from P_{DC} (power at the inverter input) and parameters k_0, k_1 and k_2, which must be fitted either from the power efficiency curve provided by the inverter manufacturer or from experimental measurements [32].

2.4 Transformer and wiring

The power efficiency of the LV/MV transformer, η_T, can be expressed as a function of the output power, P_{out}, by [33]:

$$\eta_T = \frac{P_{out}}{P_{AC}} = \frac{P_{out}}{P_{out} + P_{Core} + P_{Cu}} \qquad (7)$$

Where P_{Core} are the core losses, and P_{Cu} the copper losses, which can be calculated by:

$$P_{Cu} = P_{Cu,nom} \cdot \left(\frac{P_{out}}{P_T}\right)^2 \qquad (8)$$

Where $P_{Cu,nom}$ are the copper losses when the transformer operates at its nominal output power, P_T.

Power losses in DC and AC wiring are calculated using equations that are analogous to the Equation (8).

2.5 Energy storage

Modern electricity grids are demanding new services and technical requirements to PV systems owing to the exponential growth of penetration levels of PV technology and due to the increase in the size of the systems, whose output powers are reaching hundreds of MW.

Energy storage solutions are emerging as a mean of providing these new services by allowing the possibility of controlling the energy dispatching in different temporal scales, which may range from seconds to hours, and using different strategies, such as power curtailment, maximization of energy export or power leveling [34].

Several storage technologies are available in the current market [35], which may be simulated using a particular control strategy selected by the user. For example, limiting the rate of change of the output power ('ramp rates') for attenuating the fluctuations of PV power caused by the motion of clouds [36][37].

One of the challenges of the simulation tool is the implementation of optimization methods for the control strategies, whose techniques are widely treated in the literature (for example, reference [38] focuses on dynamic programming and briefly reviews other optimization methods).

Other major challenge that still remains is the ability of the battery models to accurately describe the real behaviour, not only in terms of their static and dynamic electric characteristics (voltage, current, state-of-charge, etc.) but also regarding its degradation and ageing.

Implemented battery models fall into two categories. The first one is the “black-box” approach, which describes the battery as a power converter characterized by its rated power, energy capacity and its conversion efficiency during charge or discharge. The second category includes models that represent the battery by an equivalent electric circuit, which are widely available in the literature, especially for lead-acid batteries.

Regardless of implemented models, it is worth mentioning that two constraints remain. First, most of battery models proposed in the literature require information beyond standard manufacturer data. And second, there is a lack of experimental validations of such models in the field, especially, when ageing models are concerned.

3 TYPES OF ANALYSIS

The simulation tool supports five types of analysis: real-time, temporal, sweep, parametric and ensembles.

Real-time analysis performs the simulation at a given instant providing the real operating conditions and state of the PV systems.

Temporal analysis, which is the most common, performs the simulation for a selected interval of time, usually a day, a month or a year.

Sweep analysis performs a variation of an input parameter over a specified range, which allows studying its influence on the system performance. For example, Figure 3 shows the energy yield of a PV system with single-vertical axis trackers as a function of the Ground Cover Ratio (GCR) [4].

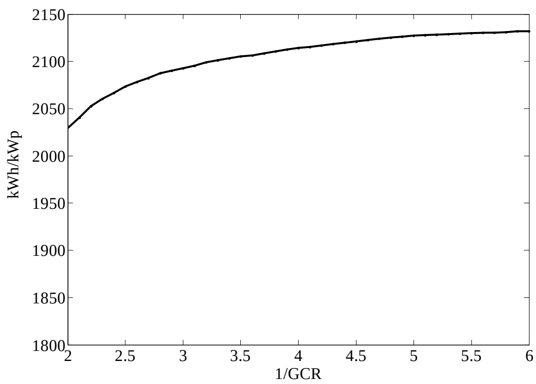

Figure 3: Energy yield, in kWh/kWp, of a single-vertical axis tracker as a function of the Ground Cover Ratio (GCR).

Parametric analysis performs several sweep analysis while varying other parameter or simulating option. For example, Figure 4 also displays the energy yield of a single-vertical axis tracker versus 1/GCR for four different cases: no backtracking (the same that Figure 3), backtracking (which moves the tracker to avoid shading) and two estimations of shading losses: ‘optimistic’, in which the losses are proportional to the shaded area (best case) and ‘pessimistic’, in which any shading cancels the PV power (worst case) [20].

In the previous analysis, simulations are performed using a single combination of models selected by the user. In contrast, the last type of analysis performs the simulations using ensembles of models for a given calculation. For example, the translation of irradiance from horizontal to inclined surfaces or the output power of the PV generator. Simulations are repeated for all possible combination of models and final results are expressed in a statistical form (average, variance, worst cases, etc.).

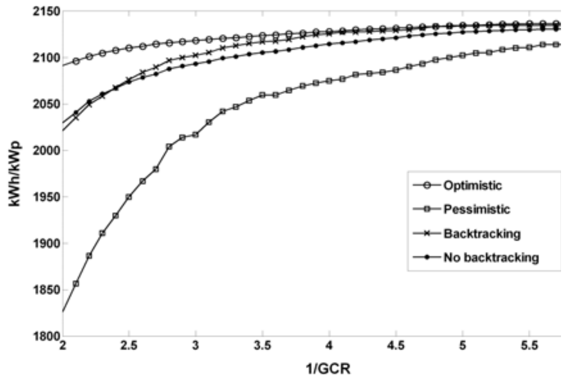

Figure 4: Energy yield (in kWh/kWp) of single-vertical axis tracker versus a GCR sweep in four cases: no backtracking (the same that Figure 3), backtracking (which avoids shading), and two estimations of shading losses: ‘optimistic’, in which the losses are proportional to the shaded area (best case) and ‘pessimistic’, in which any shading cancels the PV power (worst case).

4 OTHER FEATURES AND OUTPUT RESULTS

The tool also allows performing a standard economic and financial evaluation adapted to particular scenarios defined by legal frameworks of a country (feed-in-tariff, public support, inflation, taxes, etc.) and system characteristics (yearly degradation of PV modules, operation and maintenance costs, useful lifetime, etc.).

Despite the scope of the project [1] is the integration of PV in the electric grid, the simulation of other PV systems applications, such as stand-alone, hybrid and pumping PV systems, will be also supported.

Simulation results are expressed in the form tables, graphics or reports selected by the users. For example, Figure 5 shows a Sankey diagram, which displays the simulated energy flow across a PV system.

5 CONCLUSIONS

This paper has described the characteristics of open-source simulation tool that allows modeling, design and analyzing different types of PV systems with static or tracking structures.

Simulations are carried out using time series of irradiance, cell temperature and wind speed, obtained from the monitoring of PV systems, ground-based stations, satellite measurements, etc. Time series may be also generated by the simulator starting from monthly mean values if these are the only available data.

Models of components are based on parameters that can be obtained either from standard information (datasheets, catalogs, specifications, etc.) or from on-site experimental measurements.

Different types of analysis are supported, whose results are displayed in the form of tables, graphics or reports depending on the user needs.

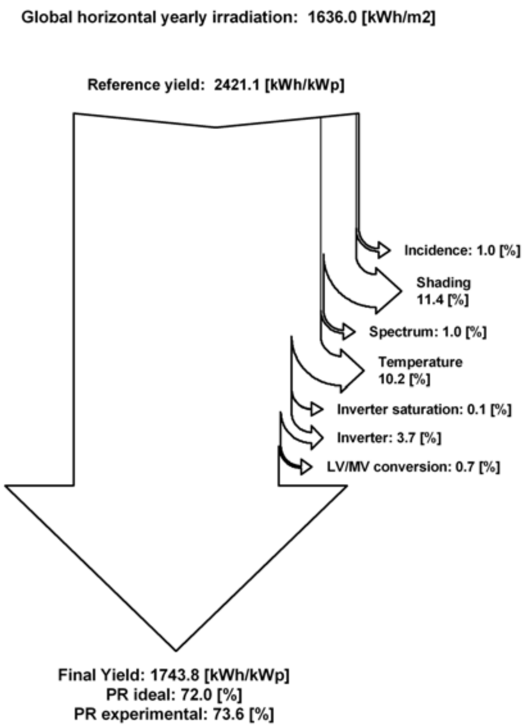

Figure 5: Sankey diagram.

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The first version of the program code, which was written in MatLab©, has been translated to PHP by Alberto Luna.

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